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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A planar cathode, Pierce-type electron gun with a design perveance of 3.2×10^{-6} A/V$^{3/2}$ has been operated with a lanthanum hexaboride (LaB$_6$) cathode. The cathode (useful diameter 1.9 cm) is heated by bombardment by electrons from a small tungsten filament. The bombardment heating system is stabilized by a feedback control circuit. The power required to heat the cathode is 315 W bombardment power and 200 W filament power. Heating power has been reduced by careful heat shielding and reduction of heat conduction losses.

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Significant additional reductions should be possible. The sintered LaB_6 cathode disk is 2.5 cm in diameter, 3.2 mm thick, and has a density of 94%. No problems have been encountered with cracking of the disk. Cathode emission is insensitive to repeated exposure to air after allowing the cathode to fully cool. The measured perveance and anode transmission of the gun are 3.2×10^{-6} and 94%, respectively. Current densities up to 6.5 A/cm^2 have been reached with 5 μs pulses. Measurements were made at cathode temperatures of 1300 to 1600° C.

ANNUAL SUMMARY REPORT ON

THERMIONIC CATHODE PROJECT

Progress Report No.3

Period Covered: Sept. 1, 1984 to August 31, 1985

by Ward D. Getty and Mark E. Herniter

Date: Jan. 9, 1986

DEPARTMENT OF ELECTRICAL AND

COMPUTER ENGINEERING

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The University of Michigan

Ann Arbor, Michigan 48109

Progress Report on Thermionic Cathode Research
Period Covered: Sept. 1, 1934 to August 31, 1985

I. Upgrade of Beam Analyzer Apparatus

The beam analyzer apparatus was greatly improved by changing from an ion pump to a turbomolecular pump. The ion pump slowly degraded over a 12 month period and became a bottleneck because it could not handle the gas load from outgassing while heating the electron gun. It also was very hard to start after opening the system and caused unacceptable delays.

To improve on this situation, a 510 liter/s turbomolecular pump and a 7.1 cfm forepump were substituted for the ion pump. The new system is a tremendous improvement, allowing much faster turnarounds on openings and handling outgassing acceptably. Experiments can begin the same day the system is closed up, and the longtime base pressure is an order of magnitude better. It now reaches 1.7×10^{-7} Torr after one or two days of pumping. With the present operating procedure, it is possible to keep the pressure below 1.0×10^{-6} Torr while heating the gun.

II. Electron Gun Design Improvements

2.1. Gun Design

A Pierce-type of electron gun was designed for this phase of the project to replace the parallel-plane diode geometry used in the first phase of the project. The primary purpose of the first phase was to develop the bombardment heating circuit used to heat the LaB_6 cathode, and to test the beam analyzer's capability for measuring beam current profiles. In the second phase a planar cathode electron gun with anode extraction hole was designed with the aid of the Herrmansfeldt-SLAC electron trajectory computer code. The electrode shapes from Pierce's original design were used as a starting point. By iterating with 8 code runs from these shapes, a

planar cathode gun with a microperveance of 3.2 and acceptable anode-cathode spacing was designed. A plot of the SLAC code trajectory results for our design is shown in Figure 2-1. The cathode diameter was chosen so that cathodes could be cut from 1-inch diameter LaB_6 rods. Taking into account the cathode edge area overed by the cathode holder, an effective cathode diameter of 0.750 inch was obtained. The remaining dimensions of the anode-cathode region were scaled from the code results.

A schematic of the present electron gun is shown in Fig. 2-2. It is mounted on a 3-inch diameter, 1/4-inch thick boron nitride baseplate. A cathode stalk of 1.25-inch-diameter, 0.020-inch-wall tantalum tubing contains the bombardment-heating tungsten filament and heat shield, and supports the cathode at one end. The cathode is mounted in a molybdenum holder and held in place by molybdenum set screws. There is a tantalum heat shield inside the cathode stalk between it and the bombardment filament. It was found that this heat shield is very important and more discussion of it will be given later. The bombardment filament is made of either pure tungsten wire or thoriated tungsten wire. The water-cooled gun anode is made of stainless steel and is also mounted on the boron nitride. The entire structure is connected to the stainless steel vacuum flange by 4 copper rods. Three electrical connections are made through two dual high-voltage feedthroughs mounted on the same 8-inch flange. The connections consist of two connections for the bombardment filament and one for the cathode. The entire gun structure and flange are removed as a unit for servicing.

The electrical connections to the gun use the same basic bombardment heating circuit as used on the Phase I diode. A general diagram of this circuit is shown in Fig. 2-3. The control circuit has been changed and will be discussed in more detail in Section 4.
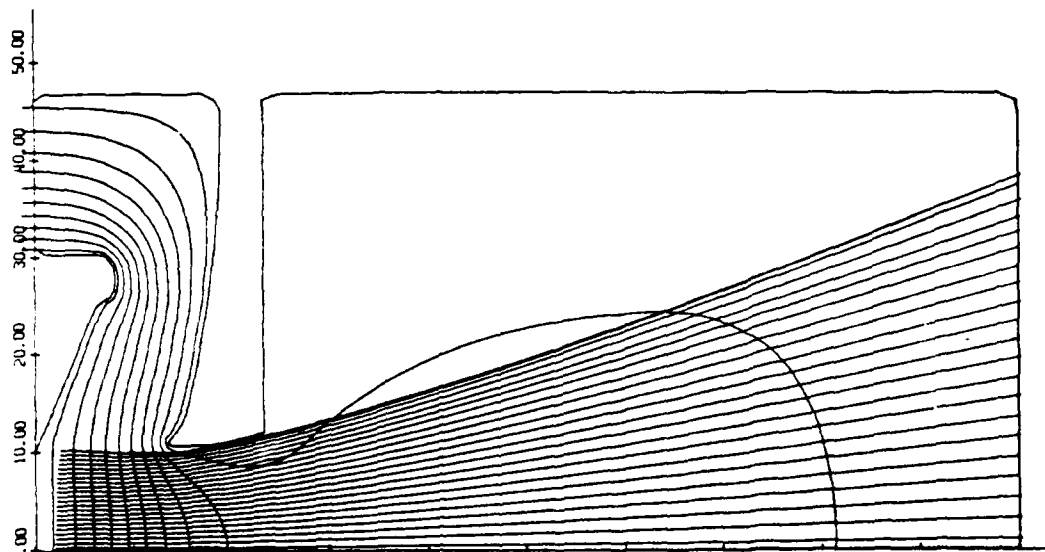
Figure 2—1. SLAC code results for the experimental electron gun geometry. The scale is set by the y axis coordinate, where 10 units = 0.375 inch. This is the radius of the planar cathode. The scale is the same in the axial direction.
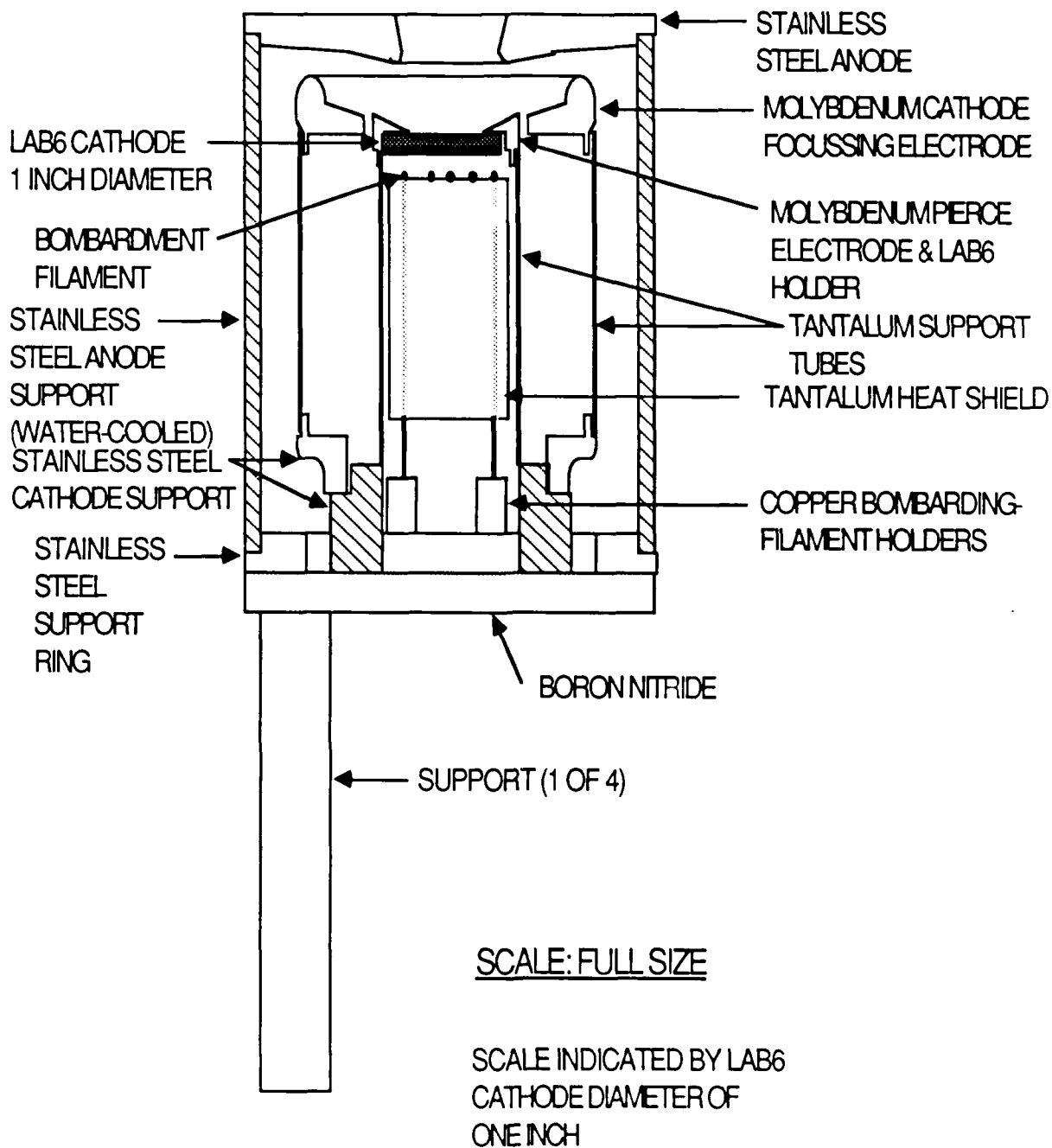
STAINLESS
STEEL ANODE

MOLYBDENUM CATHODE
FOCUSSING ELECTRODE

LAB6 CATHODE
1 INCH DIAMETER

MOLYBDENUM PIERCE
ELECTRODE & LAB6
HOLDER

BOMBARDMENT
FILAMENT

STAINLESS
STEEL ANODE
SUPPORT
(WATER-COOLED)

TANTALUM SUPPORT
TUBES

TANTALUM HEAT SHIELD

STAINLESS STEEL
CATHODE SUPPORT

COPPER BOMBARDING-
FILAMENT HOLDERS

STAINLESS
STEEL
SUPPORT
RING

BORON NITRIDE

SUPPORT (1 OF 4)

SCALE: FULL SIZE

SCALE INDICATED BY LAB6
CATHODE DIAMETER OF
ONE INCH

Figure 2-2. Assembly drawing of the UM LAB6 bombardment-heated
electron gun. Microperveance of this gun is 3.2.

System Ground

Anode

Cathode

Filament

0-500 V D.C
Power Supply
or 0 - 40kV Pulser

Triac

I_b

4Ω

Floating
Ground

120
Vac

120
Vac

| Variable Auto-transformer | Filament Transformer | Full Wave Rectifier | High Voltage Isolation Transformer | Variable Auto-Transformer |

Heating Control Circuit

120/24 Volt Step Down Transformer
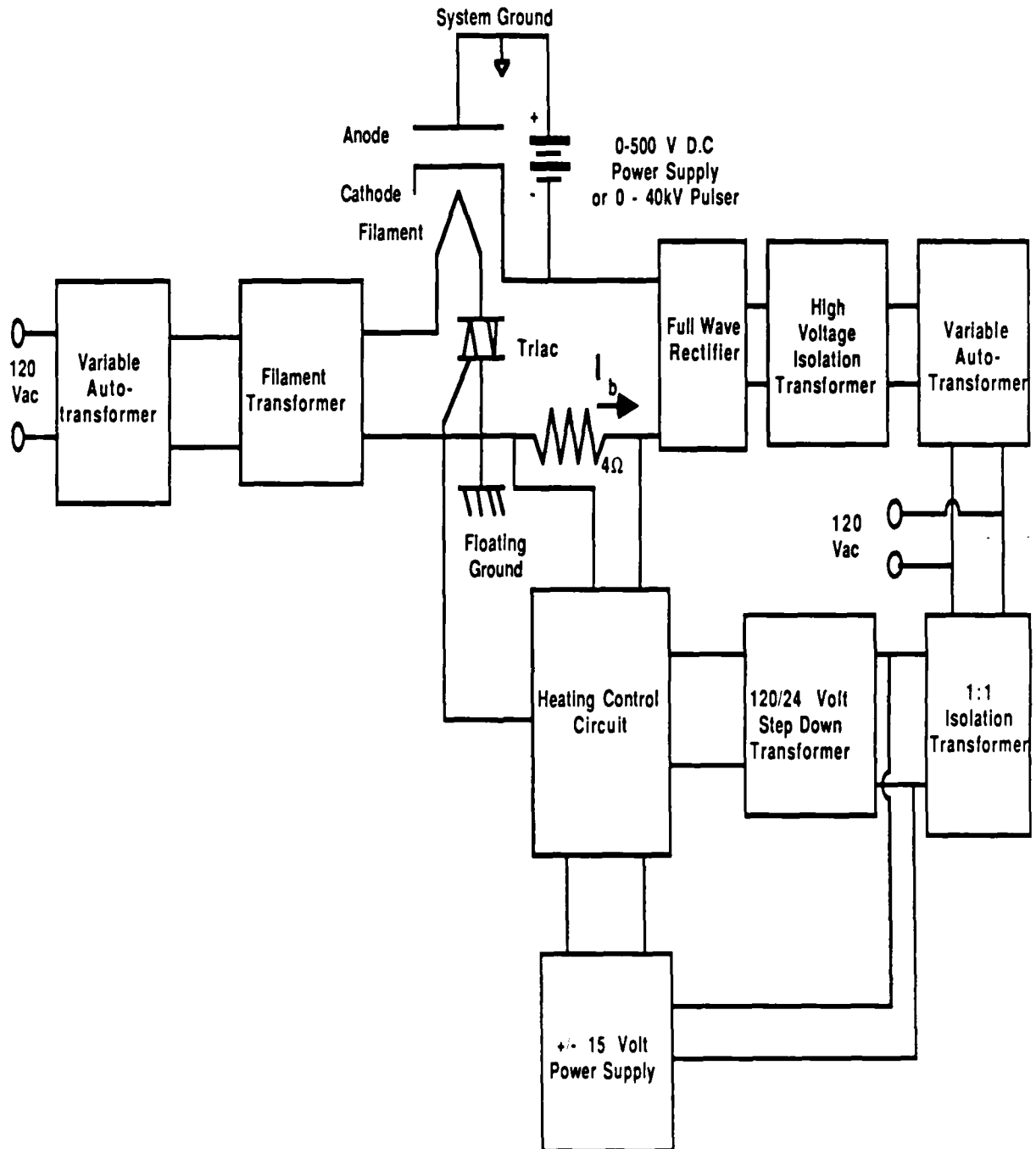
1:1 Isolation Transformer

+/- 15 Volt Power Supply

Fig. 2-3:Cathode Heating and Control Circuit

The remainder of this section presents details about the heat shield design, measurements on heating, and miscellaneous observations of cathode operation.

The present heat shield design is shown in the schematic of Figure 2-4. A tantalum cylinder (the "radial" heat shield) is supported off the boron nitride by Al_2O_3 insulators and molybdenum threaded rod. The cylinder is open at both ends but at its midsection a solid tantalum sheet (the "axial" heat shield) is spot-welded in place to completely block the cross-section except for two small holes for the filament lead wires. These wires are insulated by Al_2O_3 tubes, and are supported and held by copper connectors with set screws at the boron nitride baseplate. It was found that because of close spacing, arcing occurred between the copper connectors and the stainless steel support ring for the cathode stalk. This was eliminated by putting short Al_2O_3 tubes over the connectors. It was attempted to make the heat shield out of stainless steel tubing but it became too hot and sputtered and melted. This is not a problem with tantalum.

Electrically the shield is connected to one terminal of the filament.

The tantalum radial and axial heat shields combine to enclose the filament in a small pillbox bounded on one end by the axial heat shield and on the other by the LaB_6 cathode. This geometry improves the efficiency of use of the filament heating power because radiation from both the filament and the cathode is partially trapped in the pillbox.

The heat shield is supported by molybdenum threaded rods and Al_2O_3 tubes to take advantage of the differential coefficient of thermal expansion for these two materials. It was found that stainless steel threaded rod expanded too much and the support loosened, allowing the
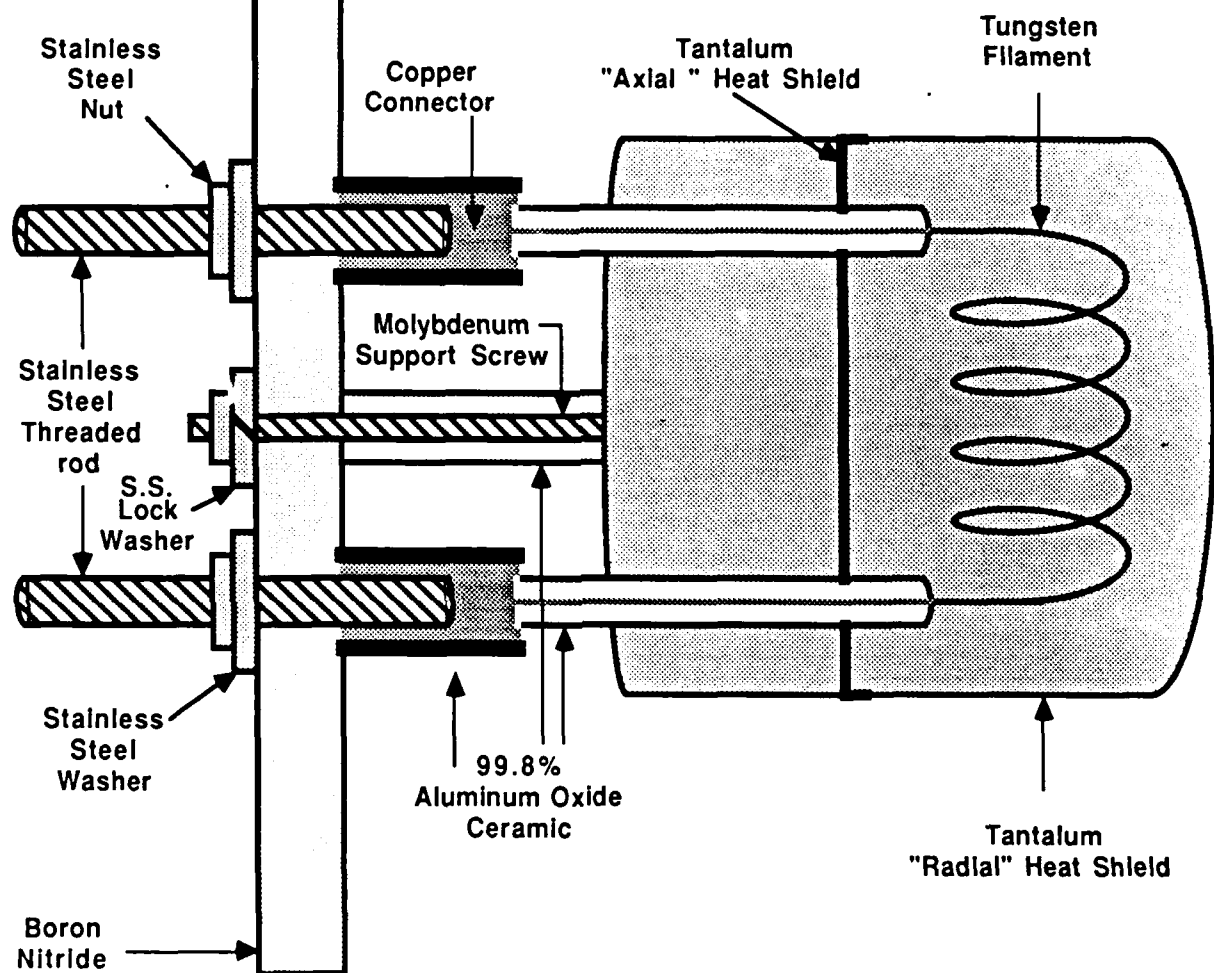
Figure 2-4: Heat Shield Assembly

shield to droop and short circuit against the cathode stalk. The potential difference between these two parts is the bombarding voltage. which varies up to 1800 V peak.

## 2.2. Cathode Heating

2.2.1. Heating Measurements

Initial operation of the electron gun was done without any heat shield. The maximum cathode temperature obtained with this configuration was approximately 1100 °C. Temperature is measured with an optical pyrometer. It was found that most of the cathode heating was done by filament radiation and a relatively small contribution was made by bombardment. By operating without the gun anode in place, it was observed that the cathode stalk was strongly heated on the cylindrical surface as well as the LaB_6 end. This indicated that a shield was needed at filament potential to prevent radial flow of bombardment current and radiation.

Another test was performed to determine the filament temperature as a function filament current. The purpose of these measurements was to determine how much current was required to reach the emission temperatures of pure tungsten (approximately 2250 °C) or thoriated tungsten (approximately 1250 °C). A plot of filament temperature versus filament current is given in Figure 2-5. The small offset in the curve above 13 A. is caused by inconsistent readings between two pyrometers. This curve was taken with the cathode removed to obtain visual access to the filament, and is therefore expected to be a lower bound since the filament radiation power loss through the anode hole will be higher than when the cathode is in place. When bombardment heating takes place the filament generally operates in the high current range in Figure 2-5. Except in a special situation to be discussed below, emission is characteristic of pure tungsten rather than thoriated tungsten.

Filament Current vs. Temperature

FIG. 2-5

Filament Temperature(°C)†
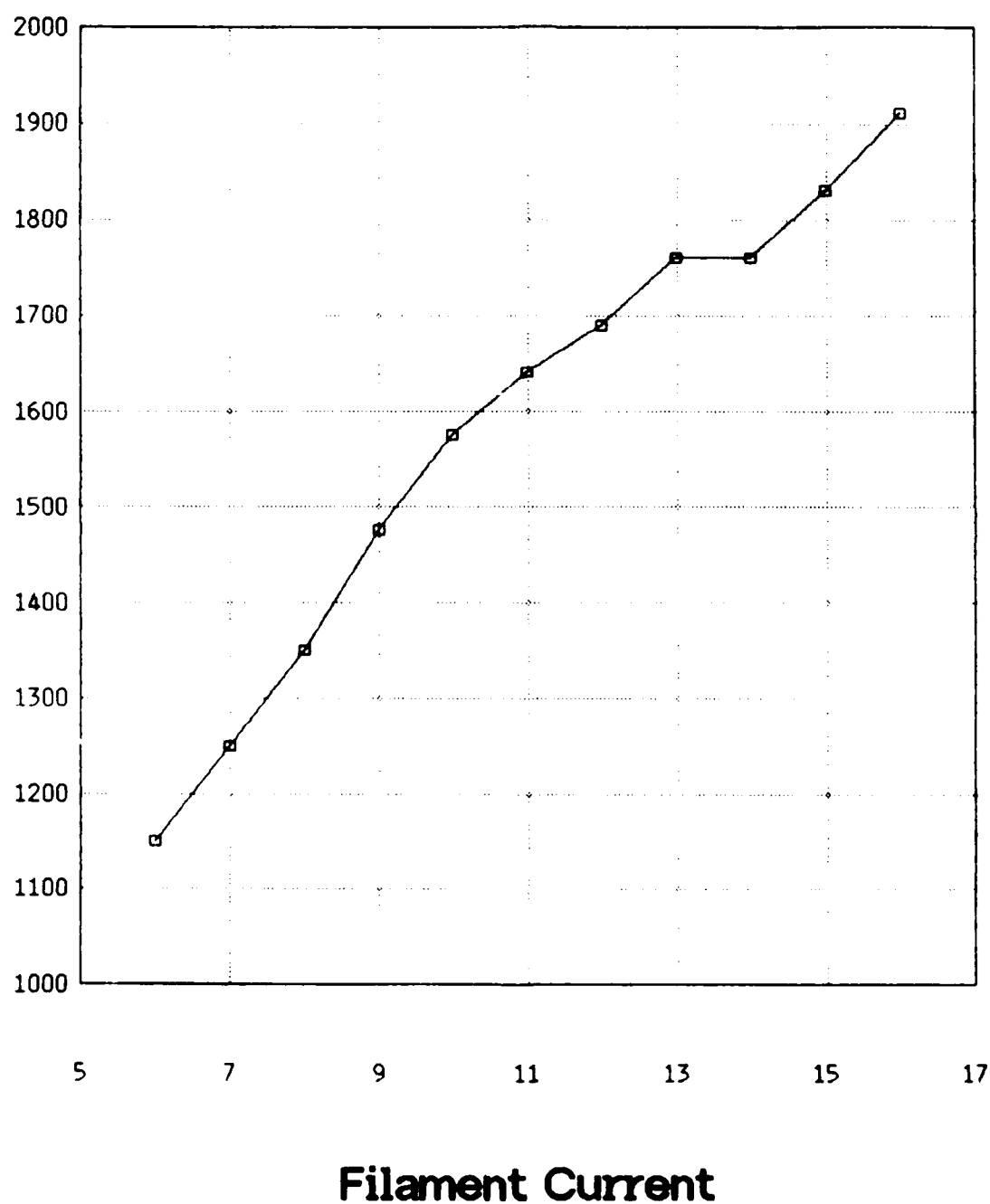
Filament Current

†Temperatures listed without emissivity correction.

With the tantalum heat shield in place, a cathode temperature of more than 1600 °C can be readily obtained. The required powers are: filament power, 200 W.; bombardment power, 300 W.; and total power 500 W. The peak bombardment voltage and current were 1200 V. and 0.75 A., respectively. Both have waveshapes like a full-wave-rectified sinusoide. The RMS filament current was 15 A., and is triac-controlled. The cathode temperature for these conditions was 1650 °C. Similar results were obtained with a stainless steel heat shield, but the heat shield could not withstand the temperature as discussed earlier in this section.

A series of measurements were made to estimate the fraction of filament power that contributed cathode heating purely by radiative heating. This was done by measuring the cathode temperature with the filament on but zero bombardment power. The filament power was also measured. Using the measured cathode temperature, the cathode heat-loss power by radiation and conduction was calculated. Assuming that this power is supplied by radiative heating by the filament, the efficiency is this power divided by the filament input power. The result is that approximately 75% of the filament power contributes to cathode heating. This large contribution makes it less important to minimize filament heating power.

A complete set of heating data is given in Figure 2-6, which shows heating power as a function of cathode temperature. The filament power, bombardment power, and total power (filament+bombardment) are shown. In this series of measurements, the onset of thoriated tungsten emission was observed at high temperatures, resulting in the downturn in the filament power at 1650 °C.

It was found that the interaction of heating power and tungsten emission was complex when the thorium was activated on the filament surface. The filaments were made of 0.020-inch diameter, 2%-thoriated

tungsten wire. Usually the effect of the thorium in lowering the work function did not seem to be present, as indicated by the large amount of filament power needed. However, it was found to be possible to activate the thorium after several hours of operation at high temperatures. Its activation may also be affected by the amount of DC current drawn from the filament and the maximum pressure allowed when the system is heated up. Further studies of this are being carried out. When the thorium effect was present the filament ran at a lower temperature and was heated sufficiently by radiation from the cathode, allowing the electrical heating power to the filament to be reduced to zero. Since thermal stability is achieved through feedback control of the filament electrical heating power, there was no feedback in this situation and the system was unstable. Quasi-stability was achievable by manually adjusting the bombardment voltage.

It was also found that feedback control was not needed when operating without thorium activation at high temperature. In this case, stability is achieved because a large amount of the cathode heating is by filament radiation instead of bombardment. The thermal instability of the bombardment system is discussed in the Annual Progress Report covering the Period 9/1/82 to 10/31/83. A theory for this sytem is being developed and preliminary results are given in Section 4.

A typical example of the effect of thorium activation is as follows: with good thorium activation, a cathode temperature of 1680 °C is obtained with 414 W. of bombardment power and zero filament electrical heating power; with a small amount of thorium activation, the same temperature is achieved with a total of 497 W., divided between 105 W. filament power and 392 W. bombardment power. With pure tungsten, a temperature of 1650°C obtained with 200 W of filament power and 300 W of bombardment power.

Heating Power vs. Cathode Temperature

FIG 2-6

Power (Watts)

Filament Power
□

Bombardment Power
▲

Total Power
◆

Cathode Temperature (°C)
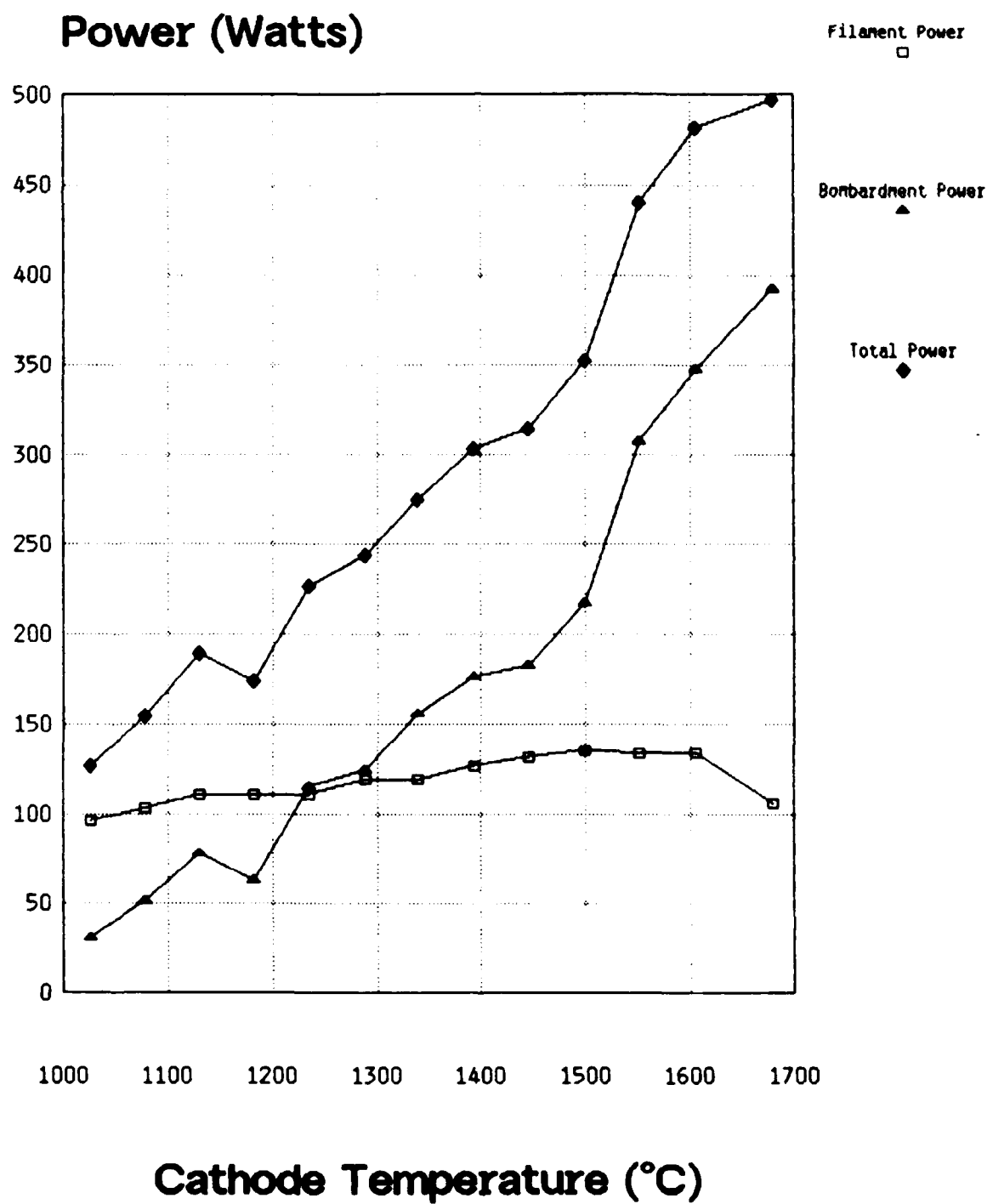
2.2.2. Cathode Heating Procedure

The same cathode was used for four months before it cracked. Cracking is caused by heating the cathode too quickly.

When 0.020-diameter pure tungsten filaments are used the following heating procedure is used:

> 1) The bombardment potential needed to achieve the desired temperature is applied while both the filament and cathode are cold.
>
> 2) The filament current is raised from 0 to 10 Amps in 2 to 3 minutes.
>
> 3) The filament current is then raised in small steps to 15 Amps in the next 5 to 10 minutes. Twenty-mil pure tungsten filaments begin to emit a bombardment current at 15 Amps filament current.
>
> 4) The bombardment current is then raised to its necessary value in the next 10 to 15 minutes by increasing the filament current.

The entire heating procedure takes between 20 and 30 minutes. Steps 1 to 3 allow the cathode to be heated to 1000°C by radiation, allowing the cathode to warm up and expand slowly.

2.2.3. Cathode Cracking Procedure

The cracking of the cathode occurred during the activation of the thoriated tungsten. Twenty-mil thoriated tungsten filaments can emit the necessary bombardment currents to heat the cathode at filament currents between 5 and 7 Amps. When steps 1 and 2 of the heating procedure were used, the cold cathode was suddenly hit with 500 W of bombardment power, causing it to crack. The stress on the cathode was so great that the cracking noise could be heard outside the vacuum system.

2.2.4. Thoriated Tungsten Filaments

The thoriated tungsten filaments were found to emit the necessary

level of bombardment current when heated with 25 - 30 Watts of filament power when the system was cold. The heat shield is designed to direct the bombardment current toward the cathode as well as limit the amount of power radiating back toward the boron nitride. The shield has the side effect of directing enough of the backward radiating power toward the filament so that the radiated power from the cathode alone is enough to heat the filament to temperatures where it can emit sufficient levels of bombardment current. This allows the system to run with no applied electrical filament power.

The activation of the thoriated tungsten became apparent after the system was heated to 1600°C for several hours. While operating with a filament currnt of 17 A, the bombardment current began to run away. The filament heating power was reduced to zero but the bombardment current did not decrease. It was found that the current could be controlled by varrying the bombardment voltage. The present control circuit cannot control the bombardment current since it requires that the filament operate temperature-limited and be heated with some minimal amount of filament power.

The method to activate the thoriated tungsten is not completely understood and requires more investigation. It has been observed that the thoriated filaments become poisoned when exposed to air while the filament is cold. After being poisoned, the filaments act like pure tungsten and need to be re-activated. This indicates that the thoriated tungsten filaments must be re-activated everytime the system is let up to air.

2.3. Miscellaneous Results

Durability. The LaB$_6$ cathode was found to be extremely durable. The same cathode was used for four months. It was only exposed to the atmosphere after cooling for at least several hours. It retained the

dark-blue color characteristic of LaB_6 on the front face, but was uniformly discolored on the bombarded side, probably by evaporated filament and stainless steel heat shield material. The cathode thickness is 0.125 inch and its density is 96 % of stochiometric density.

Temperature Uniformity. When the cathode was securely held by its holder, the central part of the cathode appeared to be at uniform temperature but the edge appeared to be slightly cooler (approximately 10 to 25 °C). When the cathode became loose, some parts of the cathode appeared to be hotter than others. The nonuniform temperature arises because the heat conduction paths away from the cathode were no longer uniform when the cathode was loose.

Arcing. A problem was encountered when the hot heat shield drooped and touched the cathode stalk, thus shorting the bombardment heating supply. This problem was mainly solved by preventing droop, as discussed in Section 2.1, and by fusing the semiconductor diodes in the power supply. The heat shield diameter had to be slightly reduced to help eliminate this problem.

III. Electron Gun Operation

This section presents results on operation at anode-cathode voltages up to 35 kV. The gun perveance P ($= I/V^{3/2}$) and the anode transmission were measured. Measured current density is compared with the Richardson-Dushman equation for thermionic emission.

3.1. Low-Voltage Operation.

The electron gun cathode is driven negative by a high-volt ge Velonex pulser in the circuit shown in Figure 3-1. The bombarding power supply and control circuit are floating from ground and follow the cathode voltage. The gun anode is grounded. In this series of measurements, the maximum voltage that could be reached was 3.5 kV. The pulse duration was 25 μs

and the repetition frequency was 60 pulses/s. A 6-inch diameter copper plate was installed in front of the anode aperture to collect current from the gun. The total cathode current was measured with a Pearson current transformer. The measured current transmission was approximately 95 % over the entire range of operation. The diameter of the witness circle made by the beam on the collector plate was in good agreement with the diameter expected from the SLAC code trajectories.

The beam cathode current as a function of beam voltage for three different temperatures is shown in Figure 3-2. Temperature limitation clearly enters at 1500 V. for a temperature of 1340 °C, but is eliminated by raising the temperature to 1445 °C or higher. As the voltage goes above 3.5 kV the cathode temperature must be raised to provide sufficient emission for space-charge-limited operation but the required temperature is consistent with the Richardson-Dushman equation. The current density reached at 3.5 kV is 0.19 A/cm^2. The effective cathode area is 2.85 cm^2. The measured microperveance for Figure 3-2 is 2.6, compared to the design value of 3.2. The curve for T=1445°C follows the 3/2-power law exactly with a microperveance of 2.6. It is believed that the reason for the lower perveance is because the cathode was loose inside the cathode holder. When lead shielding was placed around the vacuum vessel it was found that due to vibration the cathode had partially slipped out of the holder and the beam was not focussed properly.
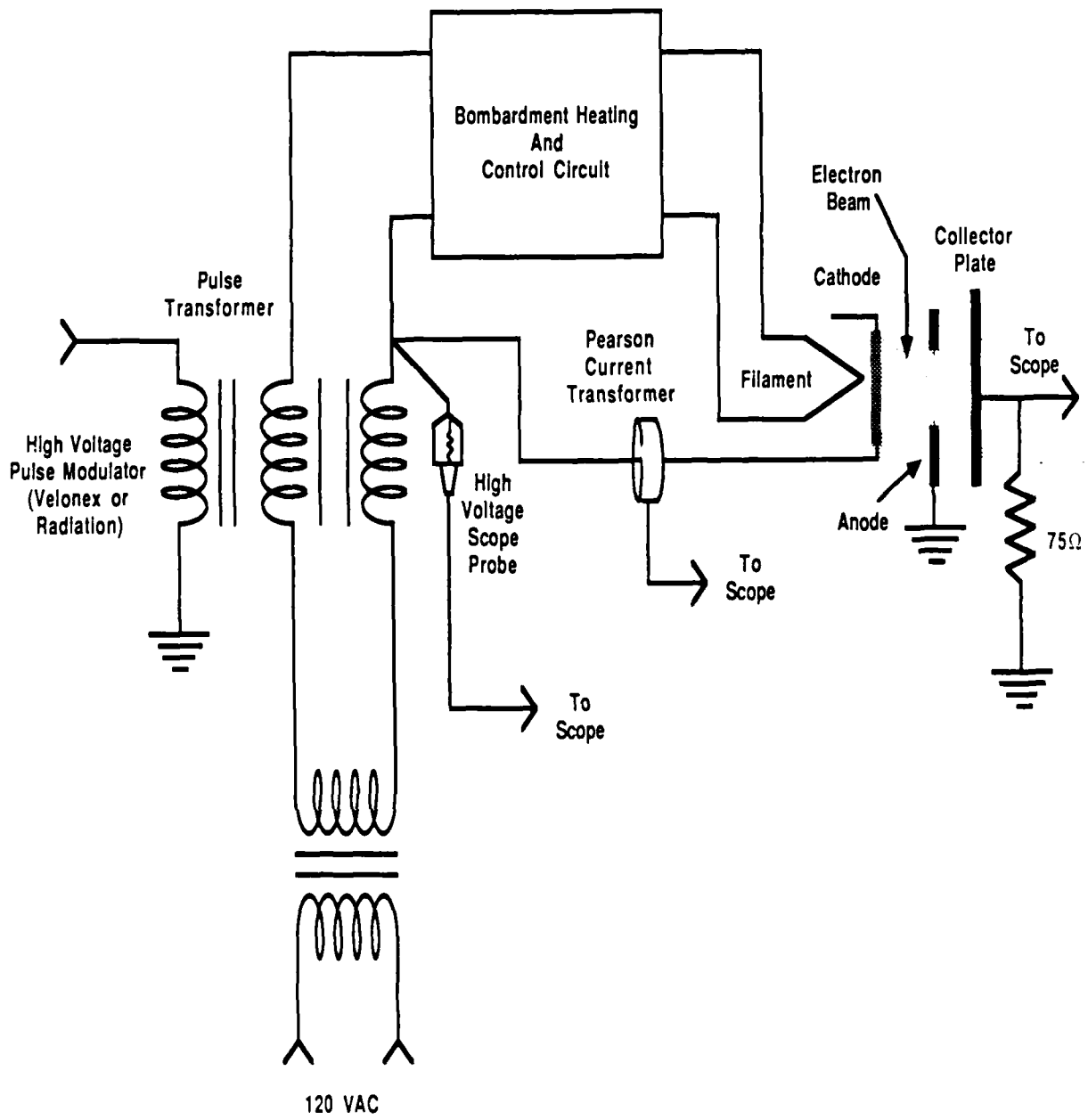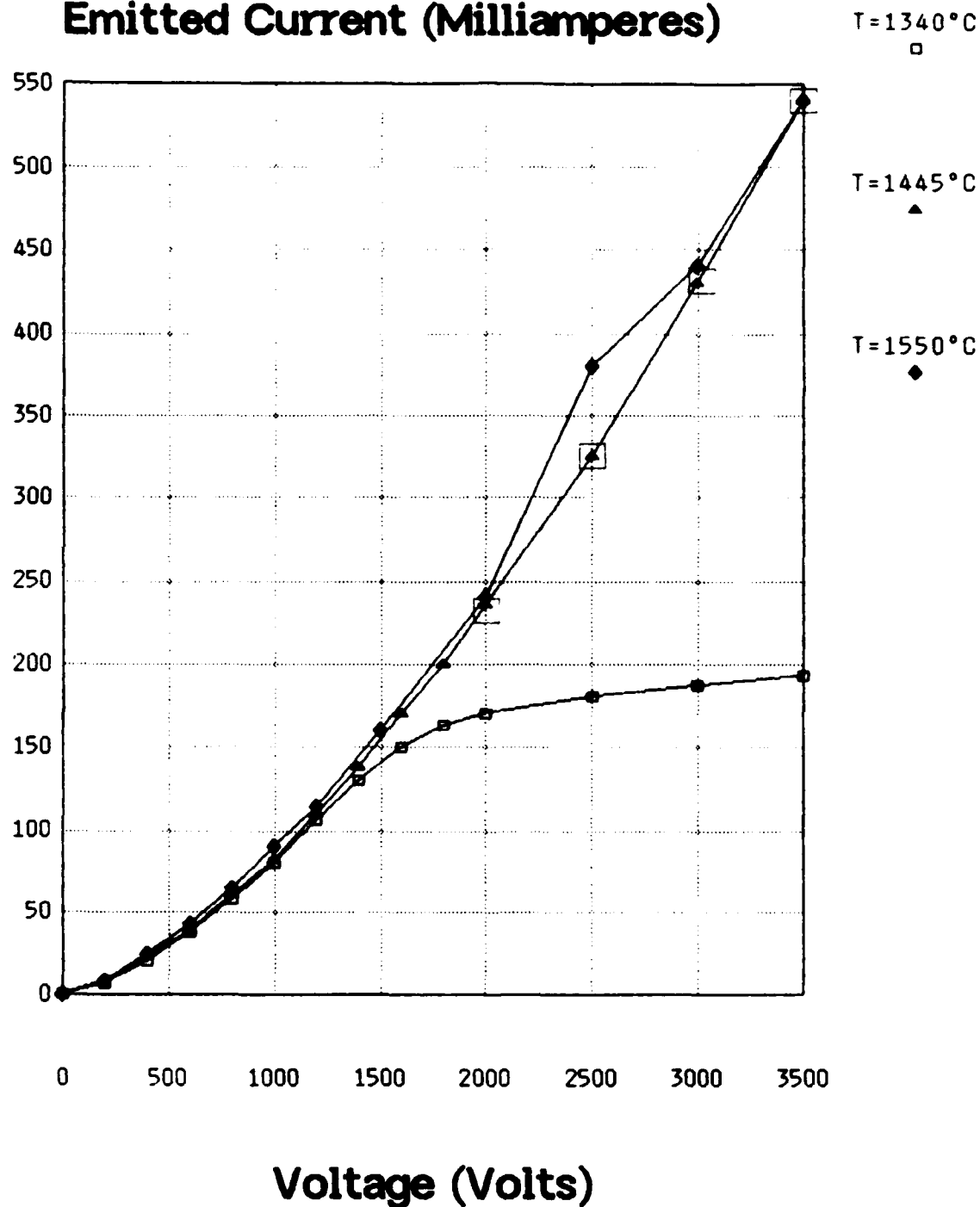
Fig. 3-1: Electron Gun Heating and Pulse Circuit

Total Emitted Current

FIG. 3-2

Emitted Current (Milliamperes)

T=1340°C
□

T=1445°C
▲

T=1550°C
◆

Voltage (Volts)

Points marked with □ are calculated assuming a microperveance of 2.6.

18

3.2.   High-Voltage   Operation

The   electron   gun   cathode   is   driven   negative   by   a   high voltageRadiation   pulse   modulator   in   the   circuit   of   Figure   3-1.   Typical current   and   voltage   waveforms   are   shown   in   Figure   3-3.   The   top   trace   is the   total   cathode   current   at   5   Amps   per   division   and   the   lower   trace   is   the cathode   voltage   at   5   kV   per   division.   The   sweep   rate   is   2 μs   per   division. A   large   amount   of   ringing,   caused   by   the   pulse   transformer,   was   present.

Current   and   voltage   measurements   were   made   with   three   different interpretations   of   the   waveforms: (1)   the   peak   negative   point   of   pulses   for several   modulator   voltage   settings,   (2)   the   average   value   of   the   pulse   in the   flat   part   near   the   trailing   edge,   and   (3)   instantaneous   points   along   a single   pulse.   The   different   interpretations   are   discussed   below.   All   data were   taken   at   a   cathode   temperature   of   1550°C.

3.2.1.   Peak   Pulse   Measurements.

This   method   gave   the   highest   current   density   of   6.5   Amps/cm^2 at   a voltage   of   35   KV.   The   effective   cathode   area   is   2.8   cm^2 and   the   perveance is 2.6×10^{-6} at   35kV.   Graphs   of   total   current   and   perveance   using   this method   are   shown   in   Figures   3-4   and   3-5.

Figure   3-3   shows   a   phase   delay   between   the   cathode   voltage   and current   which   may   be   caused   by   the   pulse   transformer.   The   delay   is   most apparent   at   the   peak   negative   point   of   the   pulse.   Figure   3-5   indicates   a relatively   large   variation   of   perveance   over   the   range   of   measured   current. This   method   of   mesaurement   may   not   be   the   most   accurate.

3.2.2.   Average   Pulse   Mesaurements.

Average   pulse   measurements   were   made   with   cathode   voltages   up to   20kV.   Higher   voltages   were   not   possible   because   of   the   large   peak   in the   waveform.   This   method   gave   consistent   measurements   of   perveance

over the entire range of currents. The measured perveance was 3.25×10^{-6} compared to the design perveance of 3.2×10^{-6}. This method gave a maximum current density of 3.29 Amps/cm^2 at 20 kV. Graphs of total current and perveance are shown in Figures 3-6 and 3-7.

3.2.3. Instantaneous Current Measurements.

In this method, photographs of current and voltage pulses were taken. Several points from one pair of photographs were used to plot cathode current versus voltage. Graphs of total current and perveance are shown in Figures 3-8 and 3.9.

Figure 3.9 shows the perveance starting to roll off at a voltage of 30 kV and a current density of 5.3 Amps/cm^2 at a temperature of 1550°C. The maximum current density was at the peak of the waveform and was the same as reported in section 3.2.1.

A variety of operating points are compared to the Richardson-Dushman equation in Fig. 3-10. The measured currents at various voltages are converted to current densities and plotted versus measured cathode temperature. In general it is found that the current density tends to follow the Richardson-Dushman equation at least up to the highest temperature and current density reached thus far.

Cathode
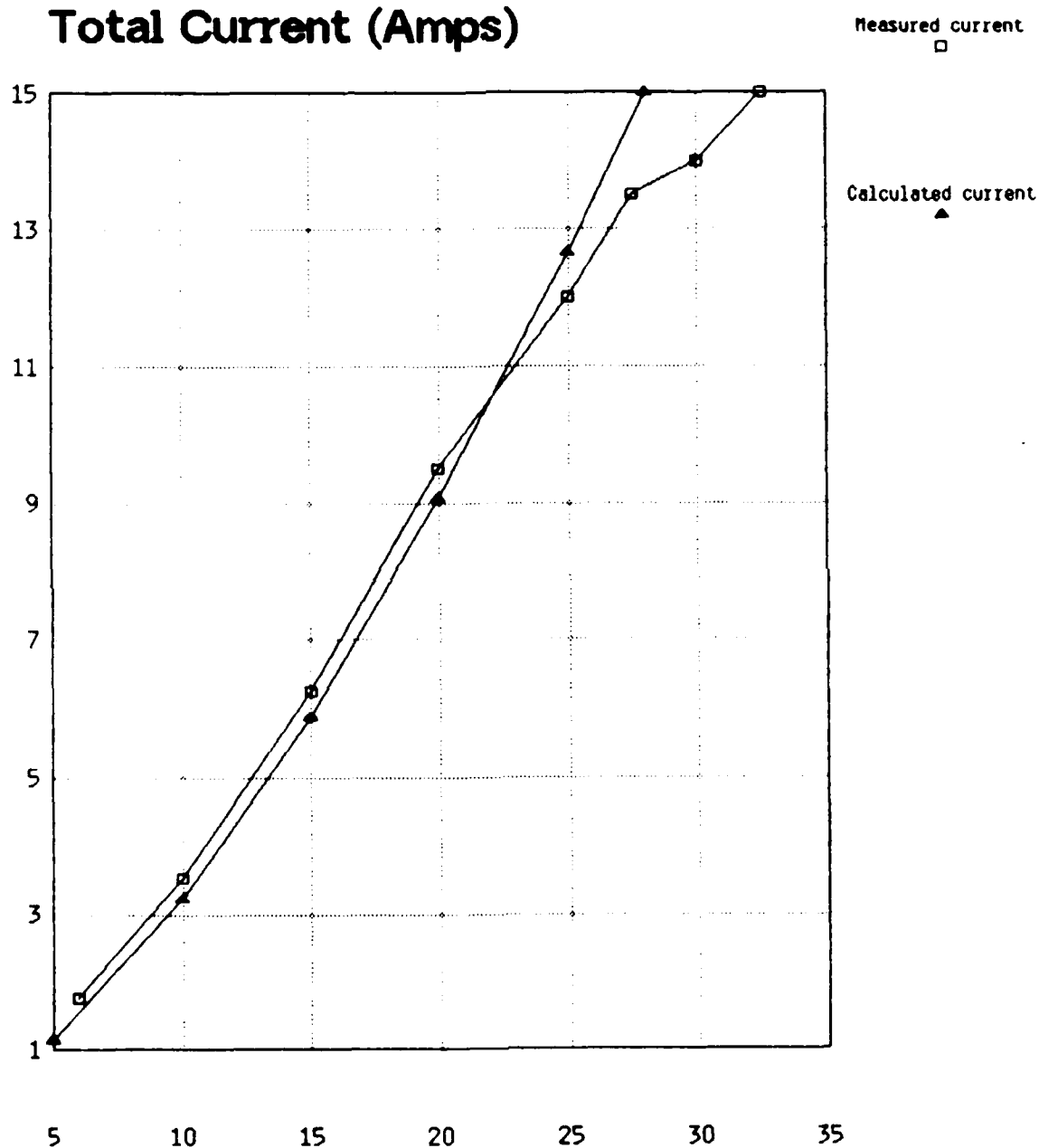Current(5   A/div)

Cathode
Voltage(5kV/div)
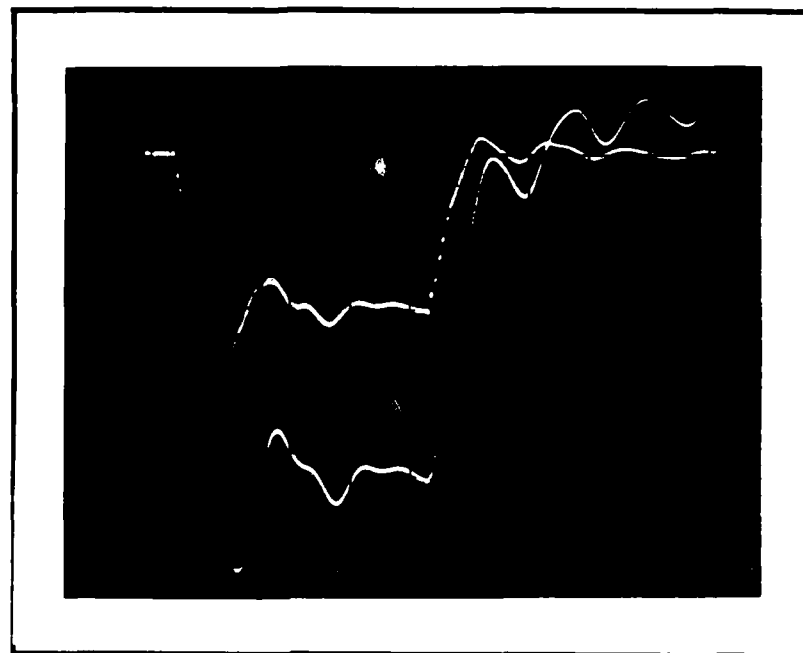
Time(2µs/div)

Fig. 3-3 : Cathode Voltage and Current Pulse Waveform

Peak Total Current vs. Voltage
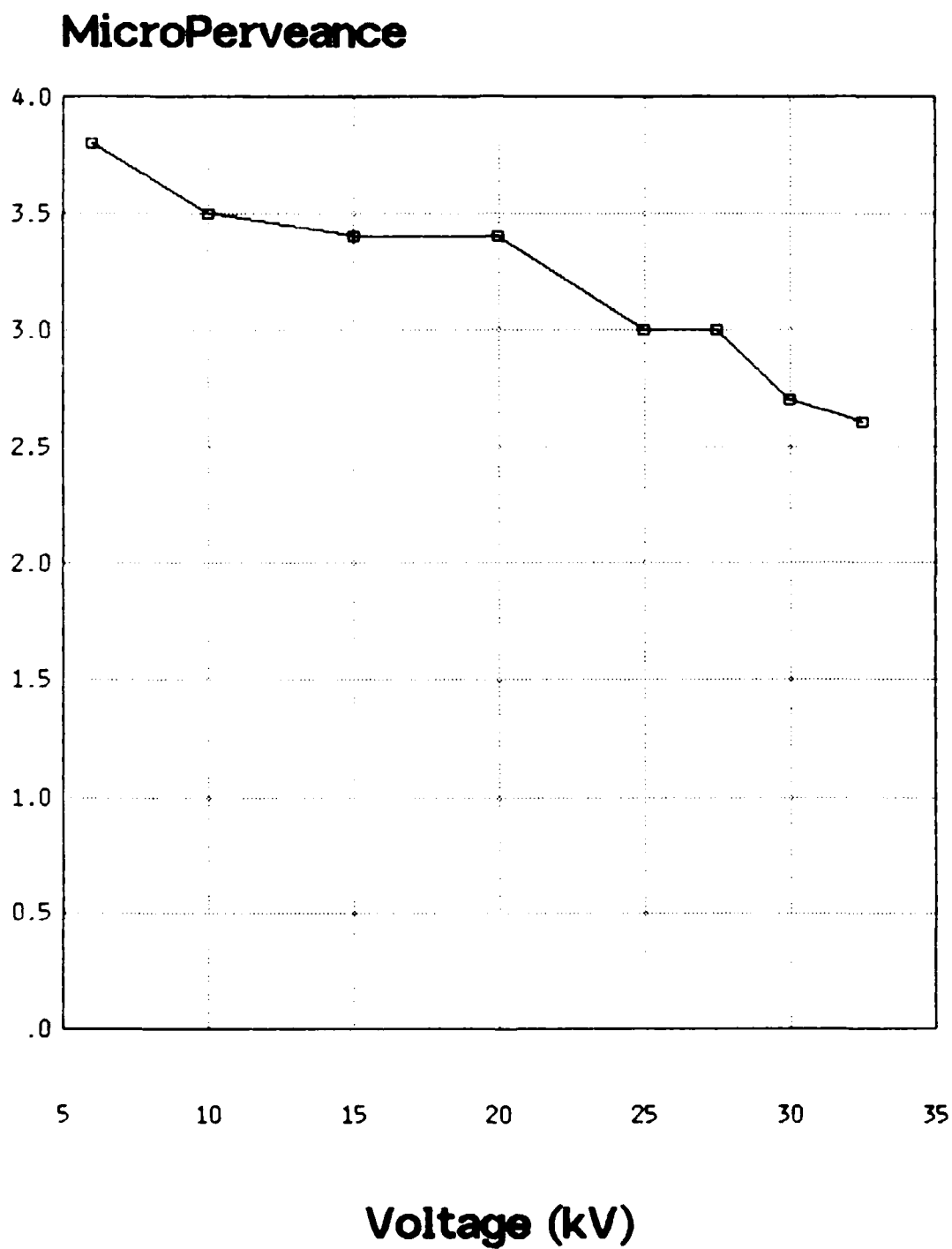
FIG. 3-4

Total Current (Amps)

Measured current
□

Calculated current
▲

Points marked by ▲ are calculated
assuming a microperveance of 3.2.

Voltage (kV)

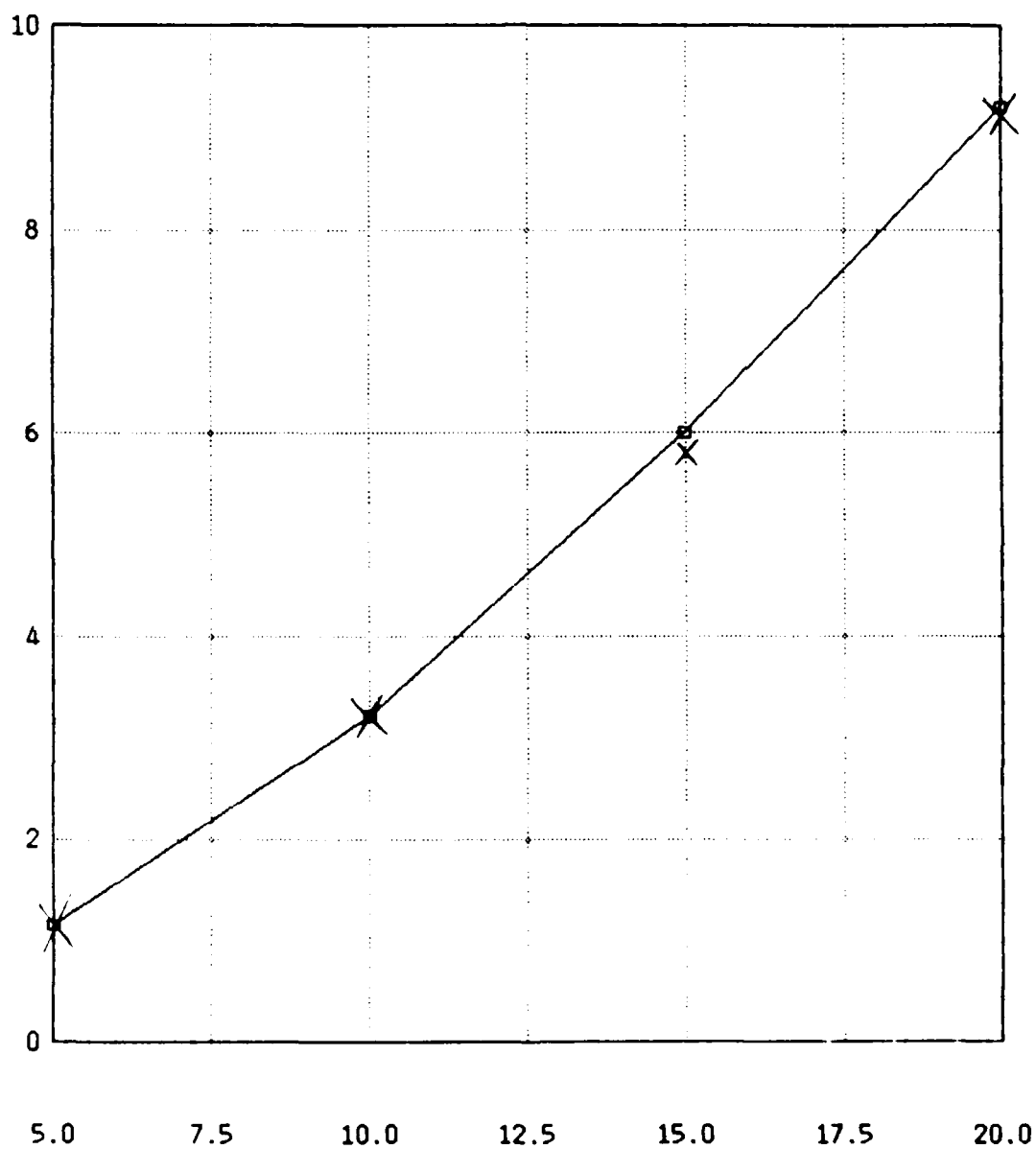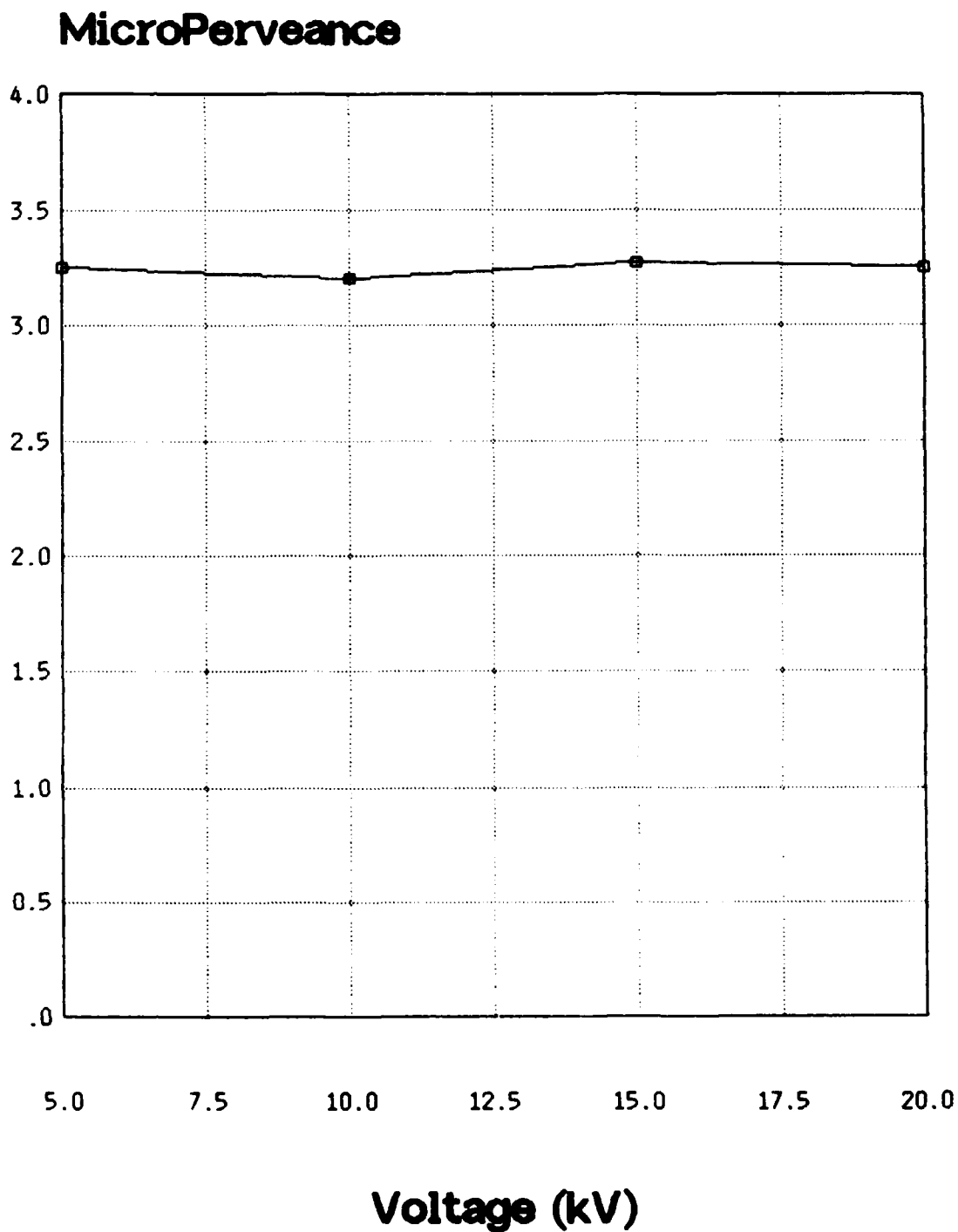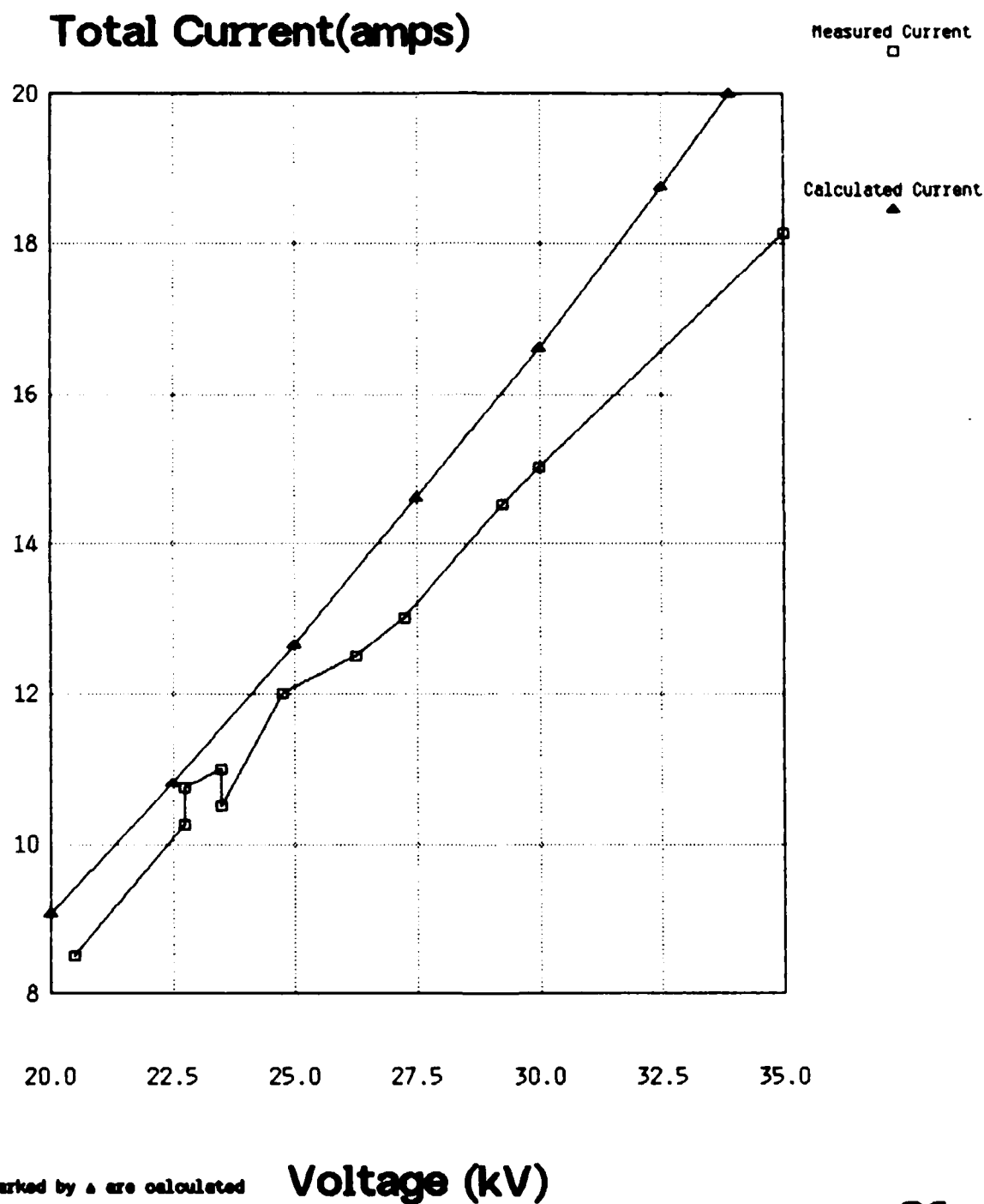T = 1550°C

22

Peak MicroPerveance vs. Voltage

FIG. 3-5

MicroPerveance

Voltage (kV)

T = 1550°C

23

Average Total Current vs. Voltage

FIG. 3-6

Total Current (Amps)

Voltage (kV)

Points marked by X are calculated
assuming a microperveance of 3.2.

T-1550°C

24

Average MicroPerveance vs. Voltage

FIG. 3-7

MicroPerveance

Voltage (kV)

T=1550°C

25

Instantaneous Total Current vs.Voltage

FIG. 3-8

Total Current(amps)

Measured Current
□

Calculated Current
▲

Points marked by ▲ are calculated
assuming a microperveance of 3.2.

Voltage (kV)

T=1550°C

Instantaneous MicroPerveance vs. Voltage

FIG. 3-9

MicroPerveance
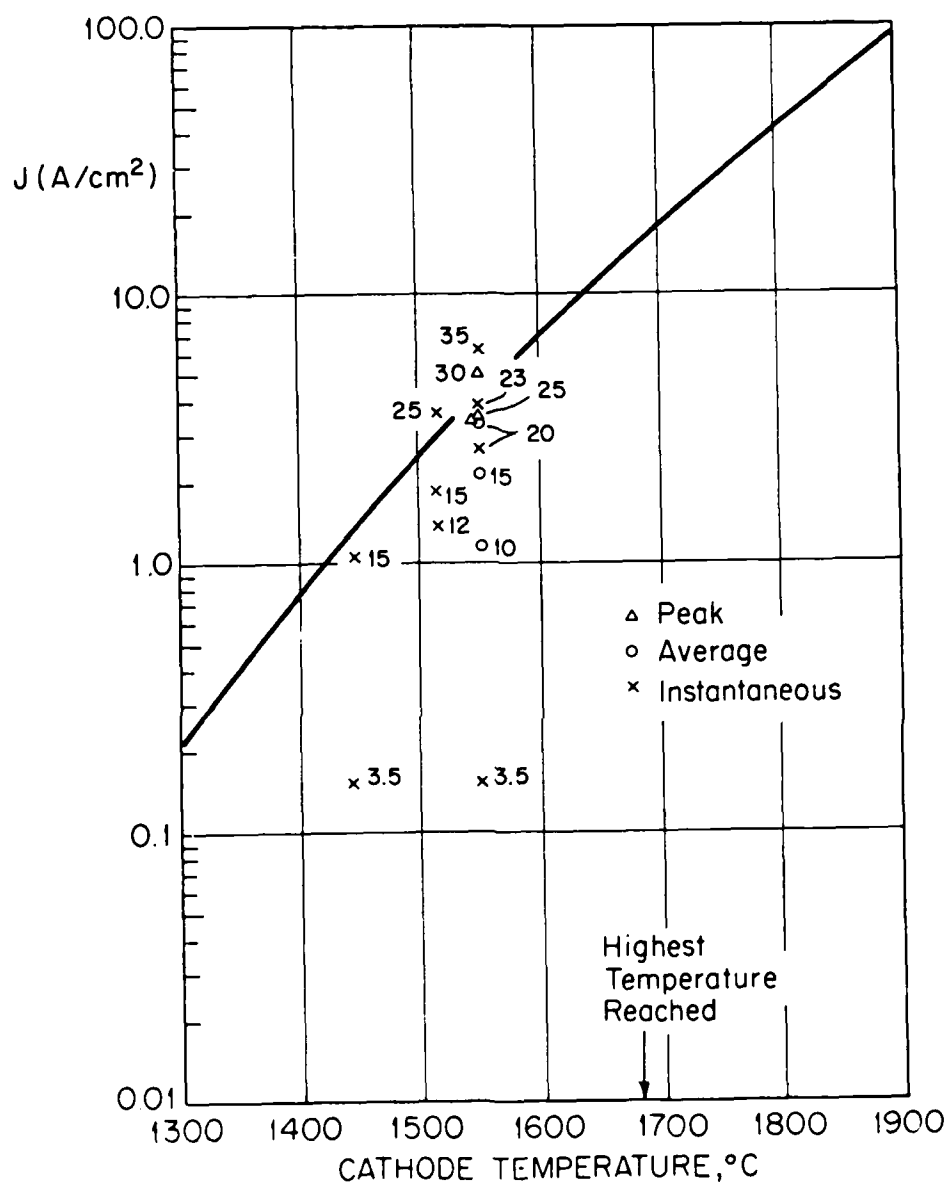

Voltage (kV)

27
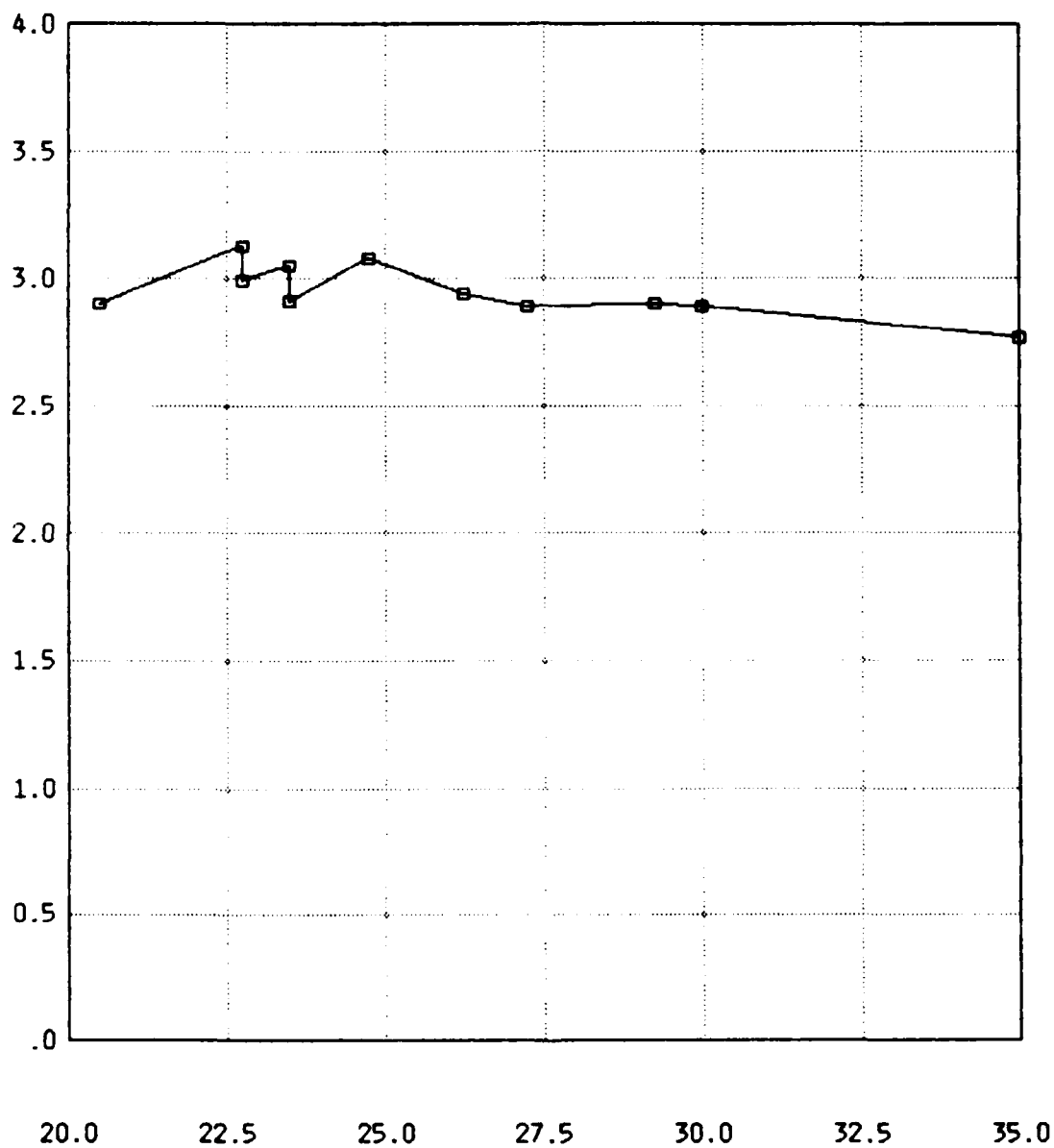
T=1550°C

Fig. 3-10 Comparison with the Richardson-Dushman equation for LaB$_6$. The solid curve is calculated from the Richardson-Dushman equation with A = 29 A/cm^2/°K^2 and $\emptyset$ = 2.66 eV. Measured current densities are plotted for several voltages ranging from 3.5 kV to 35 kV. The symbols indicate the type of current-voltage measurement (peak, average, or instantaneous) as discussed in the text. The number next to each point indicates the voltage in kV.

IV. Changes In The Control Circuit

The control circuit has been changed so that bombardment current is stabilized rather than bombardment power. The reason for this change is to obtain a "smoother" turn-on procedure. Since the bombardment voltage is derived from a low impedance voltage source, control of the current is tantamount to control of the power. Control is achieved in the same way as the earlier system by triac phase control of the filament current.
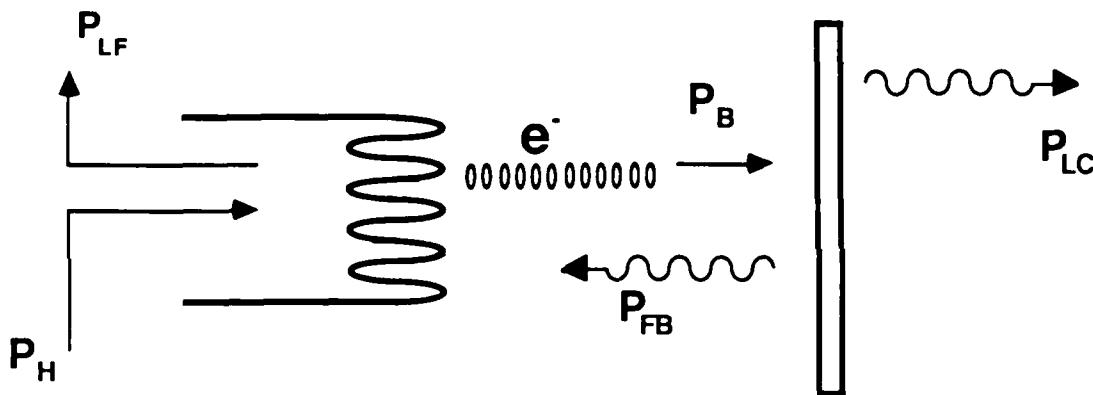

Fig. 4-1: Bombardment Heating System Model

In order to develop a theory for bombardment heating, a model is being analyzed to determine the steady state cathode temperature and to provide linearized heat transfer equations for analysis of stability. The model used is shown in Fig. 4-1. The basic power balance for the cathode is given by

$$C_c \Delta T_c = (P_{in-c} - P_{out-c}) \Delta t$$

where

C_c = change in internal energy of the cathode per

degree Kelvin.

P_{in-c} = power flowing into the cathode

P_{out-c} = power flowing away from the cathode
(power losses)

ΔT_c = change in cathode temperature in time Δt.

Power flowing into the cathode consists of bombardment power and radiated power from the filament. Power losses are due to radiation and conduction heat loss. The filament is assumed to operate temperature limited and the effect of thoriated tungsten can be included.

A similar power balance equation can be written for the filament. The resulting coupled equations are linearized, giving zero order equations for the steady-state temperatures and linear, coupled differential equations for perturbations. The linear equations predict the thermal instability found under normal conditions, and will be used as the basis for design and fine-tuning of the control circuit. The zero-order equations will be solved to determine if we can predict the power required to obtain a desired temperature.

END

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